Perceptual Issues of Augmented and Virtual Environments

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1.0 INTRODUCTION

For a sensible application of Augmented Reality (AR) and Virtual Environments (VE) it is necessary to include basic human information processing resources and characteristics. Because there is no fully functional model of human perceptual, cognitive, and motor behavior, this requires empirical analyses. Moreover, these analyses are often based on subjective ratings rather than objective measures. With regard to perception as the basic sensation of synthetic environments, each modality should be analyzed separately. There are special limits of human perception which limit the transfer of information of might even lead to unwanted negative effects or after-effects when not taken into consideration. One example for this is long exposition times and emotional inclusion of the user. They may even cause a user's isolation from the "real" daily life. In addition to a purely short-term, technological sight, it is necessary to evaluate the application of AR and VE in terms of its psychological and sociological impact.

Aspects of visual feedback are very important because of the dominance of the visual modality. The usability of the display is an important factor for the user's willingness and compliance to spend long times immersed in the virtual world. For example, HMDs need not to be too heavy, too large or too tightly fit. This category of factors groups the *General Ergonomic Factors*. The second category deals with *Physiological Factors* influencing vision. They subsume, e.g., graphics refresh rate, depth perception and lighting level influencing human performance with a VE display systems. One example is that more than 25 images per second in a dark environment cause the illusion of a continuous motion rather than single flickering images. However, the graphics refresh rates depends on the scene complexity expressed in number of polygons and shaded modality and not only on update rate of the display device itself. The third category of factors deals with *Psychological Factors* such as scene realism, scene errors (scale errors, translation errors, etc.) and the integration of feedback and command. It refers to the modification of the scene as a function of task-specific information. Markers or additional functionality can be added to the virtual world, which should help the user in performing several tasks. An example is an "intelligent agent" or tutor who serves as a figurative, anthropomorphic representation of the system status.

Acoustic feedback has a dual role. First, it is the medium for transmitting information. Second, it can be used to localize the source of the information. Ergonomic factors refer to the design of the hardware and its ease of use by humans. Physiological conditions refer to the sound frequency range which has to be within the range of audible sound (20 to 20.000 Hz) and sound intensity. If the intensity is too strong, it can produce discomfort or even, above 120 db, pain. Another factor is the sound/noise ratio. A more complex area is described by psychological factors. Sound perception and processing allows the mental reconstruction of a world that is volumetric and whose parts have specific conceptual components. A piano, for example, should not generate drum sound. Another example is a complex control panel, which concludes a large amount of visual feedback. An audio alarm can raise the user's attention to error conditions. Finally, sound or speech recognition can also be used as another, very natural input modality of the user.

Physical contact with the environment provides another important feedback. Some virtual tasks, especially manual manipulation, can only be performed accurate by adding tactile feedback to the environment.

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But this is often difficult. The aim for the future is to provide touch and force feedback to the whole body. Today, haptic feedback stimulation is usually restricted to one hand only. Fortunately, many real tasks can be carried out like this. Therefore, this restriction does no degrade human performance.

Long immersion into a synthetic environment is likely to cause several severe effects. Simulation sickness, resulting into dizziness, nausea, and disorientation is thought to be caused by a sensorial conflict between visual feedback indicating motion and the kinesthetic cuing. The phenomenon is aggravated by poor image resolution.

Factors which have been identified as contributors to simulator sickness in virtual environment systems are shown in the following Table (Frank et al., 1983; Kennedy et al., 1989; Kolasinski, 1995; Pausch et al., 1992). These are divided into characteristics of the user, the system and the user's task. Few systematic studies have been carried out to determine the effects of the characteristics of virtual environment systems on the symptoms of simulator sickness. Hence much of the evidence for the effects of these factors comes from studies of visually-induced motion sickness and motion-induced sickness (i.e., sickness caused by actual vehicle motions), as well as the effects of exposures to simulators.

**Table 2-1: Factors Contributing to Simulator Sickness
in Virtual Environments (Kennedy et al. 1989)**

User Characteristics	System Characteristics	Task Characteristics
Physical Characteristics Age Gender Ethnic origin Postural stability State of health	*Display* Contrast Flicker Luminance level Phosphor lag Pefresh rate Pesolution	*Movement through Virtual Environment* Control of movement Speed of movement
Experience With virtual reality system With corresponding real-world Task	*System Lags* Time lag Update rate	*Visual Image* Field of view Scene content Vection Viewing region Visual flow
Perceptual Characteristics Flicker fusion frequency Mental rotation ability Perceptual style		*Interaction with Task* Duration Head movements Sitting vs. standing

2.0 USER CHARACTERISTICS

Physical Characteristics: Age has been shown to affect susceptibility to motion-induced motion sickness. Motion sickness susceptibility occurs most often for people between ages of 2 and 12 years. It tends to decrease rapidly from the age of 12 to 21 years and then more slowly through the remainder of life (Reason and Brand, 1975).

Females tend to be more susceptible to motion sickness than males. The differences might be due to anatomical differences or an effect of hormones (Griffin, 1990). In a study on the occurrence of sea-sickness on a ship, vomiting occurred among 14.1% of female passengers, but only 8.5 % of male passengers (Lawther and Griffin, 1986). As seasickness is another motion-induced sickness, gender effects are likely to exist for simulator sickness as well.

Ethnic origin may affect susceptibility to visually-induced motion sickness. Stern et al. (1993) have presented experimental evidence to show that Chinese women may be more susceptible than European-American or African-American women to visually-induced motion sickness. A rotating optokinetic drum was used to provoke motion sickness. The Chinese subjects showed significantly greater disturbances in gastric activity and reported significantly more severe motion sickness symptoms. It is unclear whether this effect is caused by cultural, environmental, or genetic factors.

Postural stability has been shown to be affected by exposure to virtual environments and simulators (Kennedy et al., 1993, 1995). Kolasinski (1995) has presented evidence to show that less stable individuals may be more susceptible to simulator sickness. Pre-simulator postural stability measurements were compared with post-simulator sickness data in Navy helicopter pilots. Postural stability was found to be associated with symptoms of nausea and disorientation, but not with ocular disturbances.

The state of health of an individual may affect susceptibility to simulator sickness. It has been recommended that individuals should not be exposed to virtual environments when suffering from health problems including flu, ear infection, hangover, sleep loss or when taking medications affecting visual or vestibular function (Frank et al., 1983; Kennedy et al., 1987, 1993; McCauley and Sharkey, 1992). Regan and Ramsey (1994) have shown that drugs such as hycosine hydrobromide can be effective in reducing symptoms of nausea (as well as stomach awareness and eyestrain) during immersion in VE.

Experience: Nausea and postural problems have been shown to be reduced with increased prior experience in simulators (Crowley, 1987) and immersive VEs (Regan, 1995). Frank et al. (1983) have suggested that although adaptation reduces symptoms during immersion, re-adaptation to the normal environment could lead to a greater incidence of post-immersion symptoms. Kennedy et al. (1989) have also suggested that adaptation cannot be advocated as the technological answer to the problem of sickness in simulators since adaptation is a form of learning involving acquisition of incorrect or maladaptive responses. This would create a larger risk of negative training transfer for individuals. For instance, pilots with more flight experience may be generally more prone to simulator sickness (Kennedy et al., 1987). This may be due to their greater experience of flight conditions, leading to greater sensitivity to discrepancies between actual and simulated flight. Another reason might be the smaller degree of control when acting as instructors in simulators (Pausch et al., 1992).

Perceptual Characteristics: Perceptual characteristics which have been suggested to affect susceptibility to simulator sickness include perceptual style, or field independence (Kennedy, 1975; Kolasinski, 1995), mental rotation ability (Parker and Harm, 1992), and level of concentration (Kolasinski, 1995).

3.0   SYSTEM CHARACTERISTICS

Characteristics of the Display: Luminance, contrast and resolution should be balanced with the task to be performed in order to achieve optimum performance (Pausch et al., 1992). Low spatial resolution can lead to problems of temporal aliasing, similarly to low frame rates (Edgar and Bex, 1995).

Flicker of the display has been cited as a main contributor to simulator sickness (Frank et al., 1983; Kolasinski, 1995; Pausch et al., 1992). It is also distracting and contributes to eye fatigue (Pausch et al., 1992). Perceptible flicker, i.e., the flicker fusion frequency threshold, is dependent on the refresh rate, luminance and field-of-view. As the level of luminance increases, the refresh rate must also increase to prevent flicker. Increasing the field-of-view also increases the probability of perceiving flicker because the peripheral visual system is more sensitive to flicker than the fovea. There is a wide range of sensitivities to flicker between individuals, and also a daily variation within individuals (Boff and Lincoln, 1988).

Other visual factors, which contribute to oculomotor symptoms reported during exposure to virtual environments, have been discussed extensively by Mon-Williams et al. (1993), Regan and Price (1993) and Rushton et al. (1994).

System Lags and Latency: Wioka (1992) has suggested that lags of less than 300 ms are required to maintain the illusion of immersion in a VE, because otherwise subjects start to dissociate their movements from the associated image motions (Wioka, 1992; Held and Durlach, 1991). It is unclear whether the authors attribute these effects to pure lags or the system update rates. However, lags of this magnitude, and update rates of the order of 3 frames per second, have both been shown to have large effects on performance and on subjects' movement strategies. The total system lag in the VE-system used in the experimental studies reported by Regan (1995) and Regan and Price (1994) was reported to be 300 ms (Regan and Price, 1993c).

There is an urgent need for further research to systematically investigate the effect of a range of system lags on the incidence of simulator sickness symptoms. The interaction between system lags of head movement velocity is likely to be important, since errors in the motion of displayed images are proportional to both total lag and head velocity.

Previous studies considering hand- and head-movements show that users are very sensitive to latency changes. Subjects were able to detect latency changes with a PSE of ~50 ms and a JND of ~8 – 15 ms, respectively (Ellis et al., 1999a; Ellis et al. 1999b). When examining random vs. paced head-movements PSEs of ~59 ms and JNDs of ~13.6 ms were determined (Adelstein et al., 2003). The same values are determined with changing visual condition (background, foreground) or realism of the VE (Mania et al., 2004; Ellis et al., 2004). Pausch (1992) cites data from Westra and Lintern (1985) to show that lags may affect subjective impressions of a simulator even stronger than they affect performance. Simulated helicopter landings were compared with visual lags of 117 ms and 217 ms. Only a small effect on objective performance measures occurred, but pilots believed that the lag had a larger effect than was indicated by the performance measures.

Richard et al. (1996) suggested that the frame rate (i.e., the maximum rate at which new virtual scenes are presented to the user) is an important source of perceptual distortions. Low frame rates make objects appear to move in saccades (discrete spatial jumps). Thus, the visual system has to bridge the gaps between perceived positions by using spatio-temporal filtering. The resulting sampled motion may also result in other artifacts such as motion reversals (Edgar and Bex, 1995). Low frame rates (particularly when combined with high image velocities) may cause the coherence of the image motion to be lost, and a number of perceptual phenomena may occur, including appearance of reversals in the perceived motion direction, motion appearing jerky, and multiple images trailing behind the target. This phenomenon is referred to as temporal aliasing. Edgar and Bex (1995) discuss methods for optimizing displays with low update rates to minimize this problem.

4.0   TASK CHARACTERISTICS

Movement through the Virtual Environment: The degree of control of the motion affects general motion-induced sicknesses and simulator sickness. The incidence of simulator sickness among air-crew has been reported to be lower in pilots (who are most likely to generate control inputs) than in co-pilots or other crew members (Pausch et al., 1992).

The speed of movement through a virtual environment determines global visual flow, i.e., the rate at which objects flow through the visual scene. The rate of visual flow influences vection and is related to simulator sickness (McCauley and Sharkey, 1992). Other motion conditions that have been observed to exacerbate sickness in simulators include tasks involving high rates of linear or rotational acceleration,

unusual maneuvers such as flying backwards and freezing, or resetting the simulation during exposures (McCauley and Sharkey, 1992).

Regan and Price (1993c) have suggested that the method of movement through the virtual world affects the level of side-effects. Experiments to investigate side-effects in immersive VE have utilized a 3D mouse to generate movement (Regan, 1995; Regan and Price, 1993c, 1994; Cobb et al., 1995). This is likely to generate conflict between visual, vestibular and somatosensory senses of body movement. A more natural movement might be provided by coupling movement through a virtual environment to walking on a treadmill (Regan and Price, 1993c).

Visual Image: A wider field-of-view may enhance performance in a simulator, but also increase the risk of simulator sickness (Kennedy et al., 1989; Pausch et al., 1992). This happens although the effect of field of view is often confounded with other factors (Kennedy et al., 1989). Stern et al. (1990) have shown that restricting the width of the visual field to 15 degrees significantly reduces both. Circular vection and the symptoms of motion sickness induced by a rotating surround with vertical stripes (optokinetic drum). Fixation on a central point in the visual field also reduces the circular vection induced by rotating stripes observed with peripheral vision, and greatly reduces motion sickness symptoms (Stern et al., 1990). Circular vection increases with increasing stimulus velocity up to about 90 degrees per second (Boff and Lincoln, 1988). Further increases in stimulus velocity may inhibit the illusion. Vection is not dependent on acuity or luminance (down to scoptopic levels) (Liebowitz et al., 1979).

Linear vection can be induced visually by expanding pattern of texture points. Anderson and Braunstein (1985) showed that linear vection could be induced by a moving display of radial expanding dots with a visual angle as small as 7.5° in the central visual field. They suggested that the type of motion and the texture in the display may be as important as the field-of-view in inducing vection. The incidence of simulator sickness has been shown to be related to the rate of global visual flow, or the rate at which objects flow through the visual scene (McCauley and Sharkey, 1992). The direction of self-motion can be derived from the motion pattern of texture points in the visual field (Warren, 1976; Zacharias et al., 1985). The optical flow field appears to expand from a focal point, which indicates the direction of motion. For curved motion the expanding flow field tends to bend sideways, and the focal point is no longer defined. Grunwald et al. (1991) have shown how unwanted image shifts, which are due to lags in a flight simulator with a head-coupled head-mounted display, distort the visual flow field. In straight and level flight, the unwanted image motions which occur during head movements will cause the expanding visual pattern to appear to bend, creating the illusion of a curved flight path. The bending effect is proportional to the ratio of the magnitude of the image shifts and the apparent velocity along the line of sight. The apparent velocity depends on the velocity to height ratio. Hence the angular errors induced by the bending effect increase with decreased velocity and increased altitude.

Linear vection has been observed to influence postural adjustments made by subjects in the forward and rear direction. Lestienne et al. (1977) observed inclinations of subjects in the same direction as the movement of the visual scene movement, with a latency of 1 to 2.5 s, and an after-effect on the cessation of motion. The amplitude of the postural adjustments was proportional to the image velocity.

Interaction with the Task: Short exposure duration of less than 10 minutes to immersive virtual environments has already been shown to result in significant incidences of nausea, disorientation and ocular problems (Regan and Price, 1993c). Longer exposures to virtual environments can result in an increased incidence of sickness and require longer adaptation periods (McCauley and Sharkey, 1992). The severity of motion-induced sickness symptoms have been shown to increase with the duration of exposure to the provocation for duration up to at least 6 hours (Lawther and Griffin, 1986). Kennedy et al. (1993) reported that longer exposures to simulated flight increased the intensity and duration of postural disruption.

The extent of image position errors, and conflicts between visual and vestibular motion cues, will depend on the interaction between head motions and the motions of visual images on the display. Head movements in simulators have been reported to be very provocative (Lackner, 1990, reported by Pausch et al., 1992). However Regan and Price (1993c) found that over a ten minute period of immersion in a virtual environment, there was no significant effect of type of head movement on reported levels of simulator sickness. Sickness incidence was compared between two ten minute exposures to an immersive virtual environment. One exposure involved pronounced head movements and rapid interaction with the system. During the other exposure, subjects were able to control their head movements and their speed of interaction to suit them. There was some evidence that the pronounced head movements initially caused higher levels of symptoms, but that subjects adapted to the conditions by the end of the exposures. No measurements were made of head movements, so the effect of the instructions given to the subjects on the velocity and duration of head movements is unclear. The system lag was reported to be 300 ms, so even slow head movements may have been expected to result in significant spatio-temporal distortions. The authors suggest an urgent need for further research to systematically investigate the interaction between system lags and head movement velocity with the incidence of side-effects.

The levels of symptoms reported by seated subjects after immersion in a virtual environment have been reported to be slightly higher than the level of symptoms reported by standing subjects (Regan and Price, 1993c). However, the differences were not statistically significant after ten minute exposures.

The European Telecommunications Standards Institute has published several reports about Human Factors in many areas of computer science. In ETSI (2002) guidelines for the design and use of multimodal symbols is presented. It provides a study of the needs and requirements for the use of multimodal symbols in user interfaces, which can be also adapted to VE.

5.0   PERCEPTUAL REQUIREMENTS

5.1   Visual Requirements

Most environmental information is gained through the visual modality. The physiology of eye determines limitations and requirements for displaying information on a computer display. With current technology a faster presentation of information is possible than perception and processing of the information by the human. Therefore, Human-Computer-Interaction is mainly caused by the human operator and not the computer.

Basic visual perception starts with a projection of the image of the environment onto the retina. Special photoreceptors transform the visual stimuli into electronic stimuli. There are two different types of photoreceptors on the retina which are commonly referred to as "rods" and "cones". Rods are sensitive to light, but saturate at high levels of illumination whereas cones are less sensitive, but can operate at higher luminance levels (Monk, 1984). Rods occur predominantly near the fovea, or focal point of the eye image and the cones are more predominant around the periphery. This results into a relatively small angle of view for clear and sharp images with a size of 1 or 2 degrees only. With growing angles, sharpness decreases rapidly. Consequently, information should be displayed within this small angle. Otherwise the eye has to moving continuously in order to catch a complete glimpse. For a complete overview additional cognitive resources are required to assimilate the single views into a complete mental page. In combination with the capacity of short term memory this allows only a small amount of information that can be displayed on a single screen.

The eye's ability to distinguish color, luminance, contrast and brightness is another factor that has to be considered. The color of an object is determined by the frequency of the light that is reflected from it. The visible spectrum reaches from blue at 300 nm to red at 700nm. Different colors are obtained through

combinations of wavelengths throughout this wavelength range. Color sensitivity is created by the existence of three different types of cones in the eye: blue, green, and red. Each type of cone responds to a certain, not exact, range of wavelengths. By combining wavelengths, the human eye can distinguish more than 8,000 different colors (Monk, 1984). Approximately 8% of the male population and less than 1% of the female population suffer from color blindness to some degree. Color blindness is the inability to distinguish certain colors, notably reds and greens. This fact is also important to remember when designing visual displays for a larger user group.

Luminance is a measure of the amount of light reflected from a surface. It is determined by the amount of light that shines on an object and the reflectance of the surface of the object. Its unit of measure is Candela per square Metre (cd/m^2). Research has determined that there is a range of optimal luminance levels and that low illumination can be a hindrance to an otherwise good HCI.

Contrast is defined as the difference between the luminance of an object and its background divided by the luminance of the background (Downton, 1991). It is a measure of an eye's ability to distinguish foreground from background easily. A bright background with black writing has a low luminance for the writing and a high luminance for the background. This screen therefore, has a negative contrast. The higher the absolute value of the contrast the easier it is to distinguish objects.

Brightness is usually thought of as a subjective property of light. It depends on many factors. The main one is comparative illumination. A cloudy day may seem quite dull. The same day would be quite bright if you were just emerging from a dark room. Brightness contrast can cause several common optical illusions as well.

5.2   Special Visual Issues

There are several other issues which have to be considered when designing visual output. They are based on characteristics and deficits of human visual perception.

5.2.1   Eye Dominance

The majority of people have a distinct preference for one eye over the other. This is typically, quickly, and easily found through sighting tests (Peli, 1990). This eye dominance has shown only a limited performance advantage in military targeting tasks (Verona, 1980). Yet, the dominate eye will be less susceptible to suppression in binocular rivalry and this likelihood of suppression will further decrease over time.

An estimated 60% of the population is right eye dominant. Subsequently, it is evident that eye dominance does not correspond with users being left or right handed as only 10% of the population is left handed.

5.2.2   Pupil Adaptation

For controlling the amount of light entering the eye, the pupil will constrict (reducing the amount of light) or dilate (letting more light in). When the illumination is suddenly increased, the pupil will overcompensate by constricting and then dilating slowly to match the light level. After reducing the illumination the pupil cycles through several dilations and constrictions. Complete constriction may take less than one minute, but complete dilation may take over 20 minutes (Alpern and Campbell, 1963). This is caused partially by the fact that the cones (responsible for color perception) recover more quickly than rods (which are responsible for night vision), but have lower sensitivity. The size of the pupil will decrease once a target gets closer than I meter away (Alpern and Campbell, 1963). This is very likely due to the increase luminance caused by the light reflected off the target.

5.2.3 Visual Field

The visual field (the area the eye can perceive) is roughly 60 degrees above and below the center and slightly over 90 degrees to the outside (and 60 degrees the inside for each eye, where it is partially blocked by the nose). The lateral visual field slowly declines with age. At the age of 20 it has a size of nearly 180 degrees horizontally. At the age of 80 it is reduced to 135 degrees. Women have slightly larger visual fields then men, primarily due to differences of the nasal side (Burg, 1968).

5.2.4 Accommodation

Accommodation is the focusing of the lens of the eye through muscle movement. As humans get older, their ability (speed and accuracy) to accommodate decreases (Soderberg et al., 1993). For instance, the time to accommodate between infinity to 10" for a 28 year-old takes .8 seconds while a 41 year-old will take about 2 seconds (Kruger, 1980). The ability to rapidly accommodate appears to decline at the age of 30 and those over 50 will suffer the most. Younger humans (under the age of 20) will accommodate faster regardless of target size. However, the ability to accommodate may begin to decline as early as age 10. Accommodation for binocular viewing is both faster and more accurate than monocular viewing for all age groups (Fukuda et al., 1990). The Resting Point of Accommodation (RPA) describes the accommodation state the eye assumes when at rest. It migrates inward over time. In addition, the response time to obtain both the RPA and far point focus increase over time (Roscoe, 1985). Given these changes a VVS (**V**irtual **V**iew **S**ystem) with adjustable focus is likely to lead to improved product usability.

5.2.5 Sensitivity to Flicker

Sensitivity to flicker is highest when the eyes are light adapted. Thus users may notice flicker in the display until their eyes dark adapt. The periphery of the eye is also more sensitive to flicker and motion detection, and the closer an object is to the eye, the more likely that flicker can be detected (Kelly, 1969).

5.2.6 Vision Deficiencies

There are a wide variety of visual deficiencies in the visual system that may occur in to members of the general population. If untreated, these may lead to discomfort when using visual displays. An example of the most common of these problems will be briefly discussed in the following.

In his review of the "Private Eye" viewing device, Peli (1990) reported a large portion of the discomfort associated with the display was due to pre-existing visual conditions. This was confirmed by Rosner and Belkin (1989) who recommend a complete eye exam and correction for existing visual problems be undertaken prior to using a display system. These problems will become more prevalent with older users. Visual acuity and performance decline with age. People in their 20's tend to have 20/20 vision on average; younger subject may have 20/15 vision. With progressing age visual acuity decreases to 20/30 by age 75 (Owsley et al, 1983).

It is estimated that 3% to 4% of the general population suffer from strabismus, which describes the inability to focus both eyes to the same single point. This condition usually develops before the age of eight and is hereditary in many cases. Patients with early, untreated strabismus will also likely develop amblyopia (lazy eye phenomenon). This is a condition in which one eye will drift while the other remains focused on an object. Both lead impaired depth perception. It is estimated, that approximately 2% of the general population suffer from it (Peli, 1990).

Phoria is the tendency for a covered eye to deviate from the fixation point of the open eye. While these deviations can be very larger even after only several hours of occlusion, normal vision will return after only 1 minute (Peli, 1990). Phoria can cause the temporary elimination or reduction of stereoscopic depth perception even after both eyes are uncovered. Additional research on adults has shown that even after

eight days of one-eye occlusion subjects were able to regain normal vision hours after both eyes were uncovered. Measurable, though slight phoria was found to exist after using the "Private Eye" monocular viewing device (Peli, 1990). Changes in phoria are most likely to occur in individuals who already suffer from uncorrected visual problems (Saladin, 1988). Half of patients with near- or far-sightedness suffer from additional hyperphoria, a tendency for the eyes to drift upward. This also affects depth perception.

For the development of normal binocular vision, each eye must function well throughout the early development years during childhood. This period of development is most sensitive to disruption up to age of five years and remains critically until the age of nine years when the visual system matures (Peli, 1990). While constant use of a visual display by a person under the age of six years could lead to visual problems, it is doubtful that most of the common VR-displays can be worn comfortably by such young users. Nor is it likely that they could use such a display long enough. In addition, common AR-displays are often designed as see-through device. It is doubtful that they will attend to the monocular stimulus for a sufficient amount of time to cause permanent damage.

5.3   Audio Requirements

Although it is no question that visual is the primary modality for transferring information from a computer, practically each personal computer has a sound card today. Audio is becoming a common way of presenting additional information. Many help packages for software have an audio as well as visual component. Having a basic understanding of human hearing, capabilities and limitations also helps the designer in setting-up audio VR-components.

Hearing basically involves the same problems as seeing: Perception of environmental stimuli, translating them into nerve impulses, and combining meaning to them (Sutcliffe, 1989). At a physical level, audio perception is based on sound waves. They travel as longitudinal waves through air or other media. Sound is characterized by frequency and amplitude. Frequency determines the pitch of the sound and amplitude determines its volume. Frequency is measured in cycles per second or hertz, with 1 cycle per second equaling 1 hertz. Young children can hear in the range of about 20 Hz to over 15,000 Hz. This range decreases with age. Audible speech is between 260 and 5600 Hz – but even with a limited range between 300 and 3000 Hz communication (telephone transmission) is still possible (Sutcliffe, 1989). Speech, as well as most everyday sounds, is a very complex mixture of frequencies.

The volume or intensity of a sound is expressed in decibels (dB). This is a logarithmic expression for the ratio between the amplitude of the primary sound to the background sound and gives a measurement of the ability to hear what is intended. A whisper is 20 dB. Normal speech registers between 50 and 70 dB. Hearing loss can result from sounds exceeding 140 dB (Downton, 1991). Below 20 dB sounds can be heard, but they are not distinguishable. The ear cannot determine frequency changes below this level.

More important for acoustic perception than physical characteristics of sound is the human ability to interpret sound. The auditory centre of the cortex appears to be able to distinguish three different types of sound: background unimportant sounds (noise), background sounds that have significance (child's cry, dog's bark, etc.) and speech (Sutcliffe, 1989). Language is full of mispronounced words, unfinished sentences, missing words, interruptions, etc., but the brain still has to be able to interpret it. This seems to be done by comparison to past experience and analyzed as a stream. The same sounds can therefore be "heard" differently depending on the context. Speech is continuous. When analyzed, it doesn't appear as disjointed syllables or phonemes, but as a continuous stream that must be interpreted at a rate of between 160 and 220 words per minute (Sutcliffe, 1989).

5.3.1   Sound Perception

There are several auditory localization cues to help locate the position of a sound source in space. The first is the interaural time difference. This means the time delay between sounds arriving at the left and right

ears. The second one is head shadow. It defines the time for a sound to go through or around the head before reaching an ear. The third one is pinna response. It is the effect that the external ear, or pinna, has on sound. The forth one refers to the shoulder echo. It describes the reflection of the sound in the range of 1 – 3 kHz by the upper torso of the human body.

The fifth localization cue is caused by movement of the head. It helps to determine a location of a sound source. Another one is the occurrence of early echo response in the first 50 – 100 ms of a sounds life. Further reverberations are caused by reflections from surfaces around. The final cue is the visual modality, which helps us to quickly locate and confirm the location and direction of a sound.

5.3.2   Sound Processing

VR immersive quality can be enhanced through the use of properly cued, realistic sounds. For the design of a VR system synthetic sounds have to be generated like those in the real world. Sound processing includes encoding of directional localization cues on several audio channels, transmission or storage of sound in a certain format and the playback of sound.

5.3.2.1   *Different Types of Sounds*

Mono sound:

- Recorded with one microphone; signals are the same for both ears.

- Sound only at a single point ("0"-dimensional), no perception of sound position.

Stereo sound:

- Recorded with two microphones several feet apart and separated by empty space; signals from each microphone enter each single ear respectively.

- Perceived commonly by means of stereo headphones or speakers; typical multimedia configuration of personal computers.

- Gives a better sense of the sound's position as recorded by the microphones, but only varies across one axis (1-dimensional), and the sound sources appear to be at a position inside the listener's head.

Binaural Sound:

- Recorded in a manner more closely to the human acoustic system: by microphones embedded in a dummy head.

- Sounds more realistic (2-dimensional), and creates sound perception external to the listener's head.

- Binaural sound was the most common approach to specialization; the use of headphones takes advantage of the lack of crosstalk and a fixed position between sound source (the speaker driver) and the ear.

3D Sound:

- Often termed as spatial sound, is sound processed to give the listener the impression of a sound source within a three-dimensional environment.

- New technology under developing, best choice for VR systems.

- The definition of VR requires the person to be submerged into the artificial world by sound as well as sight. Simple stereo sound and reverb is not convincing enough, particularly for sounds

coming from the left, right, front, behind, over or under the person – 360 degrees both azimuth and elevation. Hence, 3D-sound was developed.

5.3.2.2   *3D Sound Synthesis*

3D Sound synthesis is a signal processing system reconstructs the localization of each sound source and the room effect, starting from individual sound signals and parameters describing the sound scene (position, orientation, directivity of each source and acoustic characterization of the room or space).

Sound rendering is a technique that creates a sound world by attaching a characteristic sound to each object in the scene. This pipelined process consists of four stages:

1) Generation of each object's characteristic sound (recorded, synthesized, modal analysis-collisions).

2) Sound instantiation and attachment to moving objects within the scene.

3) Calculation of the necessary convolutions to describe the sound source interaction within the acoustic environment.

4) Convolutions are applied to the attached instantiated sound sources.

Its similarity to ray-tracing and its unique approach to handling reverberation are noteworthy aspects, but it handles the simplicity of an animated world that is not necessarily real-time.

Modeling the human acoustic system with head-related transfer function (HRTF) is another approach. The HRTF is a linear function that is based on the sound source's position and takes into account many of the cues humans use to localize sounds. Here, the process works as follows:

•   Record sounds with tiny probe microphones in the ears of a real person.

•   Compare the recorded sound with the original sounds to compute the person's HRTF.

•   Use HRTF to develop pairs of finite impulse response (FIR) filters for specific sound positions.

•   When a sound is placed at a certain position in virtual space, the set of FIR filters that correspond to the position is applied to the incoming sound, yielding spatial sound.

The computations are so demanding that they currently require special hardware for real-time performance.

3D sound imaging approximates binaural spatial audio through the interaction of a 3D environment simulation. First the line-of-sight information between the virtual user and the sound sources is computed. Subsequently, the sounds emitted by these sources will be processed based on their location, using some software DSP algorithms or simple audio effects modules with delay, filter and pan and reverb capabilities. The final stereo sound sample will then be played into a headphone set through a typical user-end sample player, according to the user's position. This approach is suitable for simple VE systems where a sense of space is desired rather than an absolute ability to locate sound sources.

The utilization of speaker locations works with strategically placed speakers to form a cube of any size to simulate spatial sound. Two speakers are located in each corner of the cube, one up high and one down low. Pitch and volume of the sampled sounds distributed through the speakers appropriately give the perception of a sound source's spatial location. This method has less accuracy than sound yielded by convolving sound, but yields an effective speedup of processing, allowing a much less expensive real-time spatial sound.

5.3.2.3   Advantages and Problems

Spatial sound facilitates the exploitation of spatial auditory cues in order to segregate sounds emanating from different directions. It increases the coherence of auditory cues with those conveyed by cognition and other perceptual modalities. This way of sound processing is a key factor for improving the legibility and naturalness of a virtual scene because it enriches the immersive experience and creates more "sensual" interfaces. A 3D audio display can enhance multi-channel communication systems, because it separates messages from one another, thereby making it easier for the operator to focus on selected messages only.

However, today the costs for high-end acoustic rendering are still the biggest barrier to the widespread use of spatial audio. Especially exact environmental modeling for different auditory cues is extraordinarily expensive. Common problems in spatial sound generation that tend to reduce immersion are front-to-back reversals, intracranial heard sounds, and HRTF.

Spatial audio systems designed for the use with headphones may result in certain limitations such as inconvenience of wearing some sort of headset. With speakers, the spatial audio system must have knowledge of the listener's position and orientation with respect to the speakers. And as auditory localization is still not fully understood, developers cannot make effective price/performance decisions in the design of spatial audio systems.

5.4   Haptic Feedback

Haptic perception relates to the perception of touch and motion. There are four kinds of sensory organs in the hairless skin of the human hand that mediate the sense of touch. These are the Meissner's Corpuscles, Pacinian Corpuscles, Markel's Disks, and Ruffini Endings. As shown in Table 2-2, the rate of adaptation of these receptors to a stimulus, location within the skin, mean receptive areas, spatial resolution, response frequency rate, and the frequency for maximum sensitivity are, at least partially, understood. The delay time of these receptors ranges from about 50 to 500 msec.

Table 2-2: Functional Features of Cutaneous Mechanoreceptors

Feature	Meissner Corpuscles	Pacinian Corpuscles	Merkel's Disks	Ruffini Endings
Rate of adaptation	Rapid	Rapid	Slow	Slow
Location	Superficial dermis	Dermis and subcutaneous	Basal epidermis	Dermis and subcutaneous
Mean receptive area	13 mm^2	101 mm^2	11 mm^2	59 mm^2
Spatial resolution	Poor	Very poor	Good	Fair
Sensory units	43%	13%	25%	19%
Response frequency range	10 – 200 Hz	70 – 1000 Hz	0.4 – 100 Hz	0.4 – 100 Hz
Min. threshold frequency	40 Hz	200 – 250 Hz	50 Hz	50 Hz
Sensitive to temperature	No	Yes	Yes	> 100 Hz
Spatial summation	Yes	No	No	Unknown
Temporal summation	Yes	No	No	Yes
Physical parameter sensed	Skin curvature, velocity, local shape, flutter, slip	Vibration, slip, acceleration	Skin curvature, local shape, pressure	Skin stretch, local force

It is important to notice that the thresholds of different receptors overlap. It is believed that the perceptual qualities of touch are determined by the combined inputs from different types of receptors. The receptors work in conjunction to create an operating range for the perception of vibration that extends from at least 0.04 to greater than 500 Hz (Bolanowski et al., 1988). In general, the thresholds for tactile sensations are reduced with increases in duration. Skin surface temperature can also affect the sensitivity of sensing tactile sensations.

These details provide some initial guidance for the design and evaluation of tactile display devices in such areas as stimulus size, duration and signal frequency. For example, Kontarinis and Howe (1995) note that the receptive areas and frequency response rates indicate that a single vibratory stimulus for a fingertip can be used to present vibration information for frequencies above 70 Hz, whereas an array-type display might be needed for the presentation of lower frequency vibrations.

Additional information is available when looking at a higher level that the receptors just discussed, that is, at the receptivity of the skin itself. The spatial resolution of the finger pad is about 0.15 mm, whereas the two-point limit is about 1 to 3 mm. Detection thresholds for features on a smooth glass plate have been cited as 2 mm high for a single dot, 0.06 mm high for a grating, and 0.85 mm for straight lines. Researchers have also looked at the ability to detect orientation. The threshold for detecting the direction of a straight line has been measured at 16.8 mm. When orientation is based on the position of two separate dots, the threshold was 8.7 mm when the dots were presented sequentially, and 13.1 mm when presented

simultaneously. Reynier and Hayward (1993) discuss these findings and the results of additional work in this area. Data on the temporal acuity of the tactile sense is also reported by the authors, who note that two tactile stimuli (of 1 msec) must be separated by at least 5.5 msec in order to be perceived as separate. In general, increases in tactile stimulus duration can lower detection thresholds.

When we touch an object, typically both the tactile and kinesthetic are relevant to the experience (Heller, 1991). The object exerts a certain pressure on our hands which gives a sense of the weight and texture of the object. It also conveys a certain temperature to our hands and as we move our hands above the object, our kinesthetic sense gives information about the size of the object. Consequently, there are three basic forms distinguishable: The vibro-tactile, the temperature, and the kinesthetic sense.

The skin is sensitive to numerous forms of energy: Pressure, vibration, electric current, cold and warmth. In relation to display technology, by far the majority of the active tactile display is based on vibration. There are two major principles to generate vibration: Electrodes attached to the skin and mechanical vibration. Although both techniques are quite different, psycho-physical experiments show that the characteristics of the skin are the same for both. The human threshold for detection of vibration at about 28 dB (relative to 1 mm peak) for frequencies in the range 0.4 – 3 Hz, this decreases for frequencies in the range of 3 to about 250 Hz (at the rate of -5 dB/octave for the range 3 – 30 Hz, and at a rate of – 12 dB/octave for the range 30 – 250 Hz), for higher frequencies the threshold then increases (Shimoga, 1993b).

The perception of warmth and cold is another sensation modality. The human skin includes separate receptors for warmth and cold, hence different qualities of temperature can be coded primarily by the specific receptors activated. However, this specificity of neural activation is limited. Cold receptors respond only to low temperatures, but also to very high temperatures (above 45°C). Consequently, a very hot stimulus will activate both warm and cold receptors, which in turn evoke a hot sensation.

The literature also provides information on the just-noticeable-difference (JND) for changes of temperatures. Researchers Yarnitsky and Ochoa (1991) conducted experiments that looked at the JND of temperature change on the palm at the base of the thumb. They found that two different measurement methods gave different results, and the difference between results increased as the rate of temperature change increased. Using the more traditional measurement approach based on a method of levels, and starting at a baseline temperature of 32°C, the rate of temperature change (1.5, 4.2, and 6.7°C/sec) had no detectable effect on the JND for warming temperatures (~0.47°) or cooling temperatures (~0.2°). Subject reaction time was independent of the method used, and also independent of the rate of temperature change, although the reaction time for increases in warming (~0.7°) was significantly longer than the reaction time for increases in cooling (~0.5°). In reviewing work in this area, Zerkus et al. (1995) report on findings that the average human can feel a temperature change as little as 0.1°C over most of the body, though at the fingertip a sensitivity of 1°C is typical. He also states that the human comfort zone lies in the region of 13 to 46°C. LaMotte (1978) reports that the threshold of pain varies from 36 to 47°C depending on the locus on the body, stimulus duration, and base temperature.

Most of the research on kinesthetic perception has been focused on the perceptions of exerted force, limb position and limb movement. The kinesthetic system also uses the signals about force, position, and movement to derive information about other mechanical properties of objects in the environment, such as stiffness and viscosity (Jones, 1997). Understanding the perceptual resolution of the kinesthetic system for such object properties is very important to the design of haptic interfaces. Here is an overview of the results of studies on psychophysical scaling and JNDs for several parameters.

The subjective level of force increases with time (Stevens, 1970; Cain, 1971; Cain, 1973). The JND for force is about 7 % (Jones, 1989; Pang, 1991; Tan, 1995). The JND for stiffness (the change in force divided by the change in distance) is much higher. It is difficult to present a general value for the JND of

stiffness, since the different studies revealed considerably different JNDs. The JNDs reported vary between 19 % and 99 % (Jones, 1990; Roland, 1977). The JND values for viscosity (a change in force divided by a change in velocity, expressed in Ns/m) depend on the reference values. For small values, the JNDs are high: 83 % at 2 Ns/m to 48 % at 16 Ns/m (Jones, 1993). For higher values, the JND is lower. Reported values range from 9.5 to 34 % (Jones, 1993; Jones, 1997; Beauregard, 1995; Beauregard, 1997). Finally, the reported JNDs for mass (defined as the ratio of applied force to achieved acceleration) are relative uniform across studies: 10 % is found for weights of 50 g, and a smaller JND for weights above 100 g (Ross, 1982; Brodie, 1984; Brodie, 1988; Ross, 1987; Darwood, 1991; Hellström, 2000). For very heavy weights, the JND decreases to 4 % (Carlson, 1977).

5.5   Olfactory Feedback

The olfactory system has been researched extensively and for different purposes. The entertainment industry has also experimented with synthetic smell production, in the form of accompanying smells to enhance the experience of films (Lefcowitz, 2001, Somerson, 2001). In the Aroma Rama and the Smell-o-vision systems, smells were released in cinema theatres in certain scenes of the film. In the John Waters film "Polyester" in 1981, the audiences were given "scratch and sniff" cards and asked to release smell at certain places during the film. These experimental systems were mainly novelties and not very successful, with reactions from the audiences reaching from allergic reactions to nausea.

Those systems were all manually controlled, and the scents were all pre-produced. With respect to the inclusion of smell in the user interface, it only becomes interesting when the production of smell can be computer controlled and can be produced based on a computerized descriptions of particular smells. Then it will be possible to include olfactory displays in computer systems. For smell to gain acceptance among audiences there are many more factors that need to be in place, such as natural smelling odors, non-allergenic smells, etc.

The main idea of how an olfactory display would work is that the user has a peripheral device for smell production. This device is connected to the computer, and controlled by the computer. Using codified descriptions of smell, the computer can signal the release of a particular smell. A specific smell is generated by mixing a set of primary odors, most likely in the form of oil-based fragrances (Bonsor, 2001; Cook, 1999).

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